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Comparison of damage behaviour of different plant fibre composites under laser impact loading

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Abstract – The high strain rate behaviour of the eco-composites, when submitted to laser impact loading, is not well known yet. Crucial questions are still open: influence of plant fiber length and distribution on the composite impact behaviour, types of damage induced by impact loading, the way the failure occurs, etc. We present the very first results of a collaborative research involving the institutions PPRIME- Poitiers and PIMM-Paris, and IMP PAN-Gdansk-Poland. A comparison of laser shock induced damage is realised, based on observations of sample back faces for several types of eco-composites. Spallation, residual blister and inside delamination, depending on the fibre length in tested composites have been observed. The ability of the Terahertz technique for internal damage detection is demonstrated.

Key words: Laser shocks / eco-composites / non-destructive technique / damage analysis

1 Introduction

Global awareness of environmental issues has resulted in the emergence of “green” composites. These new materials offer eco-friendly and sustainable alternatives to classical synthetic composites, such as glass fibers reinforced polymer materials [1]. They have a lower carbon footprint and their specific properties are comparable to the ones of glass fibers due to their low density [2–4]. They already constitute attractive substitutes to glass fibers as polymer reinforcement for some semi-structural applications [5–7].

High strain rate behaviour of those eco-composites is not well known yet. In particular, their behaviour under laser shock tests has not been studied yet. The objectives of this work are to analyse the influence of plant fiber length and distribution on behaviour of these composites, and to determine the different types of damage that are induced in these materials by laser impact loading.

This study is realised in the frame of CNRS International Project, “Eco-Composites: damage Analysis Using Laser shock Technology” (PICS “ECAULT” – No. 6366). This PICS project has been established on the basis of the cooperation between three research

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This study deals with plant fibre composites made of different types of fibres (wood, flax, hemp and glass) and different types of resins (synthetic or bio-sourced, thermoplastic or thermoset). Laser shocks have been performed by means of the platform HEPHAISTOS. This short communication presents very first results. Induced damage has been analysed by observations on sample back faces, and the use of the Terahertz technique for internal damage detection has been validated.

2 Studied materials, laser shock technique and terahertz NDT technique

2.1 Studied materials

In this project, six materials are considered: five different plant fibre composites, and one glass fibre composite for comparison. Table 1 gives the description of the studied materials.

Composites with three different fibre lengths have been selected:

- with short fibres: wood fibers in polymers;
- with medium fibres: non-woven mat of flax fibers in polymers;
- with long fibers : hemp woven fabric in polymer.

Short fibre composites are made of spruce fibres and ABS polymer. Spruce fibres are from industrial waste, with average length about 800 μm . The fibre content in weight is 30%. Plates were injected with thickness of about 4 mm. Spruce fibres were used as received, or after a thermal treatment at 250 °C. These composites are noted WA or TWA.

Non-woven composites are made of flax fibers, of about 60 mm long, and polymer matrix. The flax fibre content in weight is 70%. Plate thickness is about 2 mm.

⁴ The PPRIME Institute (www.pprime.fr) develops research in the field of mechanical and aeronautical engineering. In particular, in the Department of Physics and Mechanics of Materials, researches investigate problems focused on the behaviour of composites and the laser shock technique.

⁵ The Process and Engineering in Mechanics and Materials laboratory (PIMM, Paris) (<http://pimmensameu>) has been joined, since 2009, by the LALP (laboratory for Laser Application). They develop researches in laser processes. Particularly, PIMM leads the project HEPHAISTOS with PPRIME to install a new generation of laser shock generation for LASAT Technique.

⁶ Instytut Maszyn Przepływowych of the Polish Academy of Sciences (IMP PAN, www.imp.gda.pl) has been established in Gdansk. The Department of Mechanics of Intelligent Structures, led by Prof. Ostachowicz, is particularly specialised in non-destructive damage detection methods. Recently, the group has conducted successful investigations using terahertz technique and piezo-generated guided ultrasonic waves using 3D laser scanning vibrometry.

Two types of thermoplastic polymers have been used: the polypropylene (PP), made from hydrocarbon; or the polylactide (PLA), a biodegradable polymer derived from renewable resources. These composites are respectively noted FPP or FPLA.

The two woven composite materials are made of 7 plies of a plain woven fabric impregnated with epoxy resin. The epoxy resin is an EPOLAM 2020 from Axson Technologies. Two different fabrics have been used: one is made of hemp yarns, and the other one is made of glass fibres. It leads to composites noted HE for hemp/epoxy and GE for glass/epoxy. The last composite, fully synthetic, is studied for comparison with the eco-composite ones.

2.2 Laser shock technique

The laser shock wave technique is used for testing of the studied composite materials. This technique can create a short but intense inside loading into the shocked sample. Recently, it has been applied on aeronautical composite materials and composite assemblies [8, 9]. In this study, laser shocks are performed to eco-composite materials.

The principle of shock generation by using of laser source is described in Figure 1. The laser is focused on the specimen surface. An aluminium coating forces the laser/matter interaction to be produced on the sample surface, the created high pressure plasma expands rapidly. A shock wave is generated by reaction inside the material (see in Fig. 1a). The propagation of shock waves inside material can be simply described by a schematic 1D space/time diagram (see in Fig. 1b). Shock propagates through the material according to properties depending on its characteristics and geometry. When reaching the sample back face, this incident shock wave is reflected into a release wave propagating backward due to impedance mismatch. This release wave is crossing the incident release wave coming initiated by the end of the loading (back to the initial state). This crossing of two release waves can lead to local high tensile stresses which could damage the material if the local damage threshold is exceeded.

2.3 Terahertz NDT technique

The investigated NDT technique is based on the terahertz time-domain spectroscopy (TDS). This is a spectroscopy in the frequency range from 100 GHz to around 4 THz that has been used in recent years for the purpose of non-destructive material testing. The submillimeter-waves are able to penetrate through many nonconducting materials. At each dielectric interface, e.g. from air to the composite material, the electromagnetic waves experience partial transmission and reflection. In reported work, we use the THz-TDS-system as a tool for remotely visualization of the laser caused damage. The scanning heads of the THz-TDS-system has worked in reflection mode.

Table 1. Description of the different studied materials.

Composite name	Matrix	Fibre material	Fibre architecture	Fibre content
WA (Wood/ABS)	ABS polymer	Spruce tree, as received	Short fibres randomly dispersed	30% in weight
TWA (Treated Wood/ABS)		Spruce tree, after a thermal treatment at 250 °C		
FPP (Flax/PP)	PP polymer (synthetic)	Flax	Non-woven mat	70% in weight
FPLA (Flax/PLA)	PLA polymer (bio-sourced)			
HE (Hemp/Epoxy)	Epoxy polymer	Hemp (Cannabis Sativa)	Woven fabric	7 plies
GE (Glass/Epoxy)				

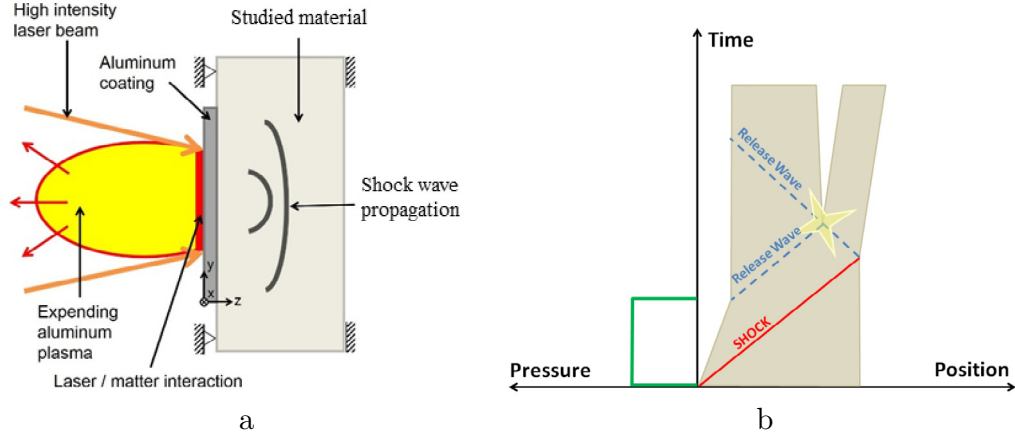


Fig. 1. (a) Sketch of the laser/matter interaction used to study the laser induced shock wave propagation into the studied material, (b) Time-position diagram representing the one-dimensional propagation of a shock and release waves into the studied material.



Fig. 2. Terahertz TDS spectrometer with scanning unit.

THz-TDS-system TPS Spectra 3000+ by TeraView Limited generates radiation in the form of repeated, very narrow pico-second pulses, which are focused and sent toward the investigated structure. Wide frequency content, small power and non-ionizing radiation are the main characteristics of the pulse. This approach is very interesting when the material allows for penetration at THz-frequencies, such as polymer composites. The experimental setup using THz TDS system is shown in Figure 2. The investigated samples are supported by steel bars mounted to system. They are responsible for the movement in the horizontal plane.

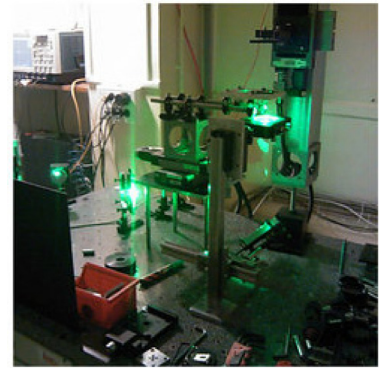


Fig. 3. HEPHAISTOS laser facility.

3 First results

In this study, laser shock tests have been performed using HEPHAISTOS laser facility (Fig. 3). Laser shocks with several intensity levels have been realised on the different studied materials. The focused laser beam had a diameter of 6 mm, and the pulse duration was 10.2 ns.

In Figure 4, is shown the residual damage that are visible on back face surface of each composite after a laser impact with intensity value of around 4.5 GW/cm² are shown. In short fibre composites, WA and TWA, there is a separation and ejection of fragments from the surface, which is named the spallation phenomenon. This phenomenon does not cover the same area for the two

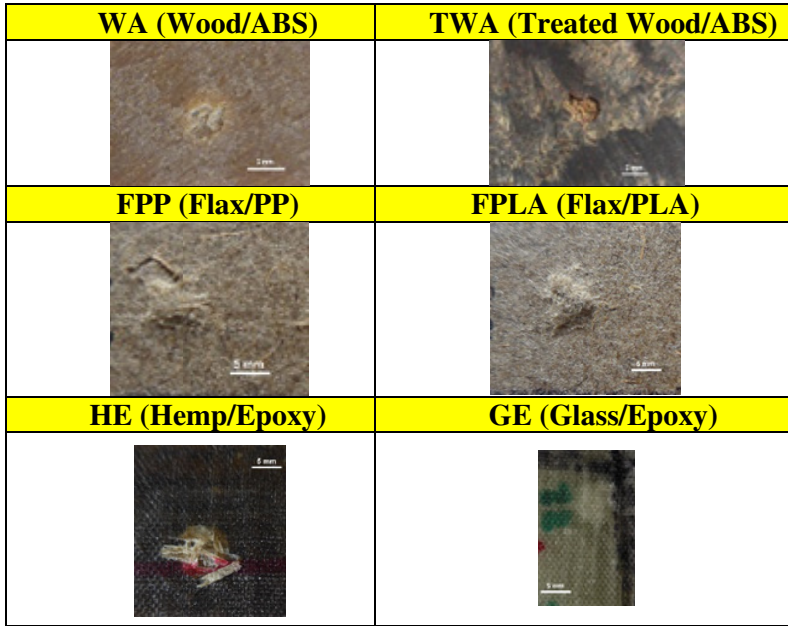


Fig. 4. Residual damage visible on back face surfaces of each composite for a laser impact with intensity of around 4.5 GW/cm^2 (bar scales of 5 mm long).

composites: the diameter of the spallation zone is about 4.7 mm in WA, whereas it is about 6.8 mm in TWA. This result seems to demonstrate that the thermal treatment of spruce fibres leads to a higher brittleness of the composite, when it is submitted to high strain rate loading. For composites with flax mat reinforcement, no spallation is observed (Fig. 4). The inside damage induced by the laser shock creates a residual relief, leading to small blisters on the back face surfaces of these two composites. Measurements of the diameter values of these blisters show that there is also a difference between these two composite behaviours. For the FPP sample, the blister diameter value is about 8.5 mm, and it reaches 10 mm for the FPLA sample. It shows that laser shock induces larger damage in the composite with PLA matrix than in the one with PP matrix. In Figure 4 are also presented the results obtained for the two woven composites. On the hemp/epoxy composite, a blister with partial spallation is visible, with a diameter of about 9.4 mm, whereas on the glass/epoxy material only a whitened zone can be seen, with a diameter of about 7.7 mm.

These results show that studied composites exhibit very different behaviours when they are submitted to laser impact loading, depending on the type of fibres, on their length and distribution, and on the used matrix.

First results of terahertz NDT technique were obtained for WA sample. The exemplary time domain signal registered is presented in Figure 5. The initial peak (about 15 ps) represents the strong reflection for the upper sample surface. The reflection from the bottom of the sample is visible at about 60 ps. In order to perform a NDT assessment the sample was scanned with a fine grid of measurement points spaced by 0.25 mm. The scanning result is presented in Figure 6 in a form of a C-scan. The colours represent the peak-to-peak values of time signals

(Fig. 5). The strongest reflection is observed in lower left corner at which a metallic tape was placed for referential purposes. The clear presence of surface damage is visible due to sudden drop of the signal value at position (5.0 mm, -10.0 mm). The lower intensity shocks caused less pronounced damage visible at $y = 0.0 \text{ mm}$ in the range from $x = 0.0 \text{ mm}$ to 40.0 mm.

These results show that the terahertz technique can be used for studying this type of eco-composites because the THz radiation penetrates the sample. Due to this fact, it is foreseen that not only the surface damage can be characterised but also the internal damage, non-visible on the sample surface.

4 Conclusion

This short communication presents very first results obtained by applying laser shocks on plant fibre composites. They show that damage behaviour at very high strain rate of these materials is directly linked with the type of fibres, their length and distribution, and the type of matrix. For the same laser impact intensity, three types of damage have been observed on back face samples: spallation, residual blister and inside delamination. Short fibres lead to spallation phenomenon, which shows their low strength. Non-woven fibres lead to residual blister, which is the damage step preceding the spallation. Woven hemp fibres lead to a combination of blister and spallation, whereas woven glass fibres lead to inside damage, whitening the back face surface. Moreover, results also show that the type of matrix plays a role in the damage area size. In addition, this work demonstrates the ability of Terahertz technique for analysing damage inside the composites, showing with different intensities inside

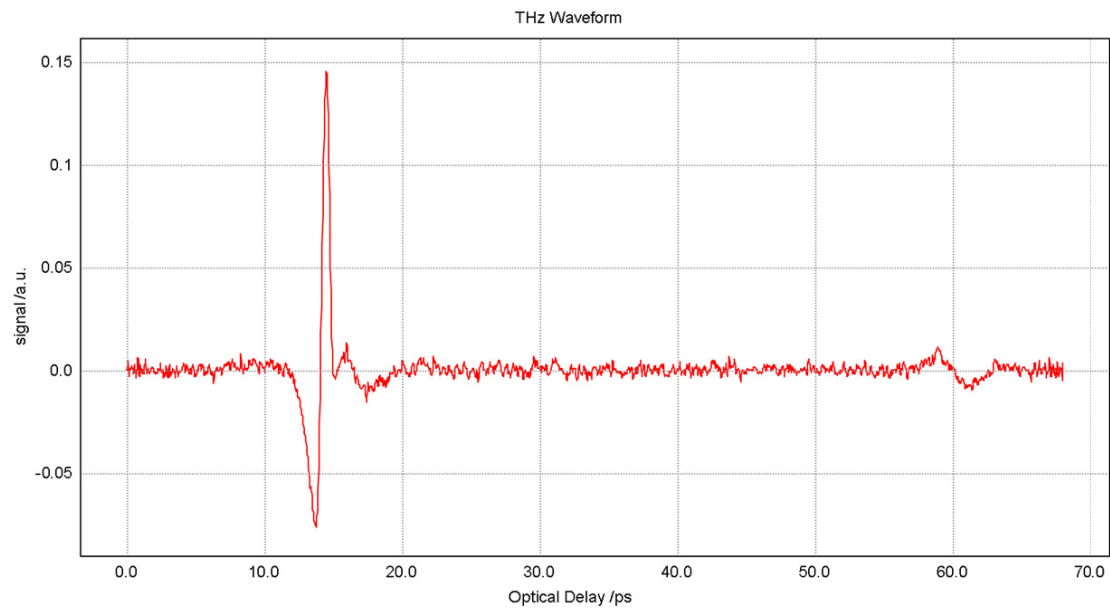


Fig. 5. Time domain signal from the terahertz spectroscopy.

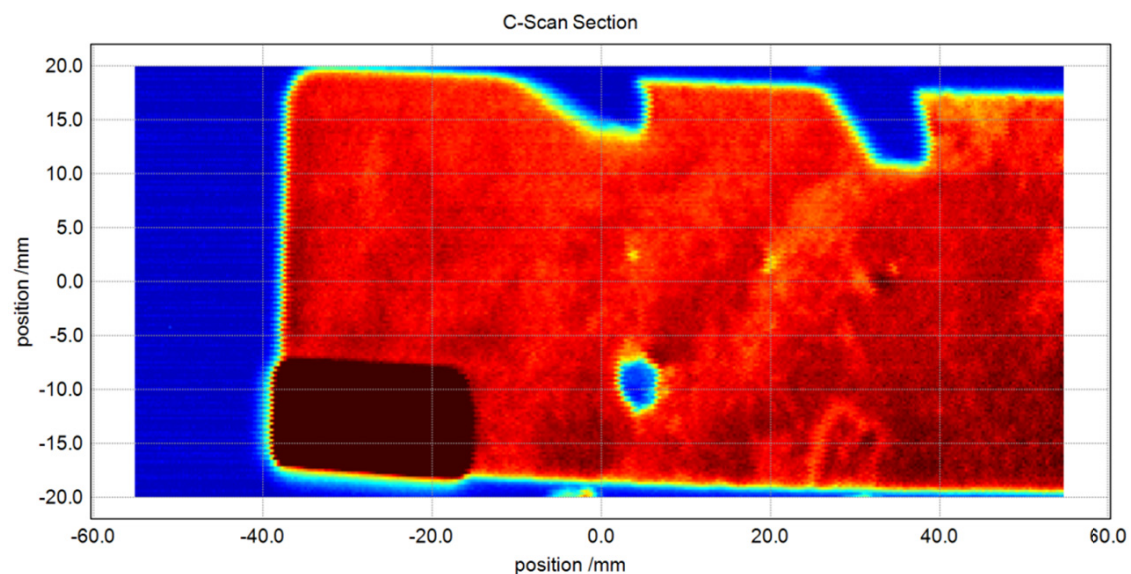


Fig. 6. Peak-to-peak C-scan of the WA sample obtained using terahertz technique.

damage created by different energy levels of laser shocks. This research project is ongoing, with the use of different techniques for damage observations and analysis. It is planned to use other non-destructive techniques (NDT). These methods have already been used for other types of materials [10–13]. In particular, a method based on a piezoelectric transducer for wave excitation and a laser vibrometer scanning for wave sensing will be used on the studied eco-composites. Then, samples will be cut and polished for microscopic observations. Finally, this international collaboration will give complete data concerning the damage behaviour under laser shock of these “green” composites.

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